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ENVIRONMENT INTERACTION TECHNOLOGY**

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LARGE SPACE SYSTEM - CHARGED PARTICLE ENVIRONMENT

INTERACTION TECHNOLOGY

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ABSTRACT

Large, high voltage space power systems are being proposed for future space missions. These systems must operate in the charged-particle environment of space and interactions between this environment and the high voltage surfaces are possible. Ground simulation testing has indicated that dielectric surfaces that usually surround biased conductors can influence these interactions. For positive voltages greater than 100 volts, it has been found that the dielectrics contribute to the current collection area. For negative voltages greater than -500 volts, the data indicates that the dielectrics contribute to discharges. Using these experimental results a large, high-voltage power system operating in geosynchronous orbit was analyzed with the NASCAP code. Results of this analysis indicated that very strong electric fields exist in these power systems. A technology investigation is required to understand the interactions and develop techniques to alleviate any impact on power system performance.

INTRODUCTION

Large space systems are being proposed for future applications such as manufacturing, technology demonstrations, communications and beaming power for Earth usage (refs. 1-6). These systems are proposed for operations in orbits ranging from low Earth orbits (200 to 400 km) to geosynchronous. These future applications will require space power systems capable of generating from 25 kW (ref. 7), to multikilowatts (ref. 8), to gigawatts required for the Solar Power Satellite (SPS) (refs. 4 and 5). Since the power level is proportional to the surface area, these power systems will be large with dimensions ranging from 10's to 100's of meters.

It will be necessary for these power systems to operate at elevated voltages to reduce line losses and minimize system weight (ref. 9). At operating voltages in the kilovolt range, interactions with the charged-particle environment are possible. Since the highest operating voltage reported for satellites to date is 100 volts (ref. 10), there is limited space experience to guide the system designer in constructing a high voltage space power system. There has been ground testing of biased surfaces in plasma environments to determine possible interactions

(refs. 11-19) and several analytical treatments of the impact of these interactions on performance (refs. 20-25). Due to the limited facility size and complex insulator/conductor geometry of solar arrays, these experimental and analytical treatments can only serve as indicators of what might happen. While probe theory can be used to compute biased-conductor current collection, the tests have shown that the insulation surrounding the conductors does have a profound influence on the collection phenomenon. The role of the insulator in this interaction must be understood before corrective techniques can be devised to minimize the impact of the interaction on system performance.

The interactions of concern are illustrated in the high voltage space power system shown in figure 1. This system consists of two large solar array wings surrounding a central body or spacecraft. Depending upon the physical size factors, this system could represent a "direct-drive" solar electric propulsion spacecraft (i. e., one in which the high voltage needed for the electric thrusters is generated directly on the solar array wings - ref. 26) or a SPS. In either case the solar arrays are assumed to be assembled in what is called standard construction techniques. This means that the cover slides do not completely shield the metallic interconnects from the environment. These cell interconnects are at various voltages depending on their location in the array circuits. Hence, the interconnects can act as plasma probes attracting or repelling charged particles. At some location on the array, the generated voltage will be equal to the space plasma potential. Cell interconnects at voltages above this space plasma potential will collect electrons while those at voltages below the space potential will collect ions. The voltage distribution in the interconnects relative to space must be such that these electron and ion currents are equal (i. e., the net current is zero). This flow of particles can be considered to be a current loop through the power system to space that is in parallel with the operating system on the spacecraft and hence, is a power loss.

The severity of this plasma-coupling current depends upon the operating voltages of the power system and the charged-particle environment. Since the proposed missions consider voltages up to a maximum of 45 kV, the electric fields from exposed surfaces at these voltages will only attract the lower energy components of the environment (i. e., the "thermal plasma"). This environment (see fig. 2) has particles with temperatures of about 1 eV and densities that vary from a maximum of 10^6 cm^{-3} at about 300 km to between 1 and 10 cm^{-3} at geosynchronous altitude. Hence, one should expect current coupling to be more severe at lower altitudes and only a very high voltage concern at geosynchronous conditions.

Interactions with the charged-particle environment are not limited to plasma-coupling currents. The possible confinement of voltages (and electric fields) to cavities formed by the cover slides and interconnects could conceivably give rise to breakdowns in the negative voltage regions. The large, high power systems are proposed as rather flexible arrays mounted on thin, dielectric substrates. Operations at high voltages could exceed the dielectric strength of the substrate material giving rise to additional breakdowns. In either case these breakdowns would produce transients in the power system.

Finally, the electric fields established in the dielectric substrate and cover slides can induce substantial forces in these materials. These forces must be considered in building a high voltage space power system.

In this report the ground experimental work is reviewed to provide indicators for the interactions that could exist in the space power system. A preliminary analytical model of a large, space power system is constructed using the existing NASA Charging Analyzer Program (NASCAP) and its performance in geosynchronous orbit evaluated. These analytical results are used as to illustrate the regions where detrimental interactions could exist and to establish areas where future technology is required.

GROUND SIMULATION TEST RESULTS

Tests have been conducted using samples biased by laboratory power supplies to determine the interactions with plasma environments. Results have been reported by several investigators (refs. 11-19) and the data is in reasonably good agreement. For this report the test data from the Lewis Research Center (LeRC) experiments is used to summarize the characteristics of the interactions.

Test Procedure

Tests at the LeRC have been conducted in a 1.8 m diam \times 2.5 m long vacuum facility and a 4.6 m diam \times 16 m long facility. A nitrogen plasma is generated in a bombardment source and allowed to drift into the chamber. The plasma particles have a temperature of about an electron volt and densities that can be controlled from about 10^6 cm^{-3} to 10 cm^{-3} . The plasma properties are measured before and after each run with diagnostic instruments (i. e. probes and Faraday cups). The ambient pressure in both chambers, while the sources are operating, is about 10^{-6} torr.

The solar array segment used in these tests is shown in figure 3. This is a 100 cm^2 segment consisting of 24 solar cells in series mounted on a fiberglass board. During the tests in the simulation vacuum chamber, the segment is mounted such that it is electrically isolated from the chamber. Electrical leads from the segment are brought out of the chamber with high-voltage feed-throughs. These leads are connected first to an ammeter and then to a bias power supply. The power supply is referenced to the chamber which acts as the electrical ground. The circuit is completed to the segment through the plasma. The plasma coupling current collected by this segment at a given bias voltage is measured by the ammeter. The cover slide and interconnect surface voltages are measured by a capacitively-coupled probe sweeping 3 mm above the segment (ref. 17). The test arrangement is shown schematically in figure 4.

Larger solar array panels with 2000 cm^2 area have also been tested in a similar manner. A series of tests have also been conducted on a solar electric propulsion array segment utilizing wrap-around interconnects. The difference between

the wrap-around and standard (or conventional) interconnects is shown in figure 5. The results from both these test samples will be discussed in the following section of the report.

Ideally, testing should be conducted with the solar arrays themselves generating the desired voltage while floating electrically within the chamber. However, in order to study interactions in a typical series-parallel circuit solar array a large panel would be required. Such a solar array panel would have to be tested in a correspondingly large vacuum facility to minimize the interfering effects of chamber walls. Since such facilities are often difficult to obtain, this type of testing would make a good candidate for a Shuttle experiment.

Test Results

The plasma collection currents collected over a range of plasma densities for the 100 cm² solar array segment is shown in figure 6. The data shown in figure 6(a) is for the electron coupling currents obtained when the segment is biased positive with respect to chamber ground while the data in figure 6(b) is for ion coupling currents obtained with the segment biased negative.

When the test segment is biased positive at voltages less than +100 volts, the electron current collection is low. Comparisons between this data and probe theory predictions indicate that the collection at a given bias voltage and with given plasma properties is dependent only on the interconnect area. In this voltage range, the electron current collected by a segment increases uniformly with bias voltage. As the bias voltage is increased above +100 volts, this relationship breaks down and there is a sharp increase in the electron current collection. When the bias voltage exceeds +250 volts, the electron current collection again behaves as before, only with current collection, at given bias voltages and plasma properties, now being dependent on the entire panel area. This behavior occurs at all plasma densities from the simulated geosynchronous environment ($\sim 30 \text{ cm}^{-3}$) to the 900 km environment ($\sim 10^4 \text{ cm}^{-3}$). Other tests with this segment have indicated that electron current collection with a given surface area increases linearly with bias voltage up to 20 kV.

Why does this transition in electron current collection occur? The answer can be found in the surface voltage traces obtained during these tests (see fig. 7(a)). At bias voltages of less than 100 volts, the quartz cover slides assume the slightly negative voltage necessary to maintain a net zero current. This quartz surface voltage appears to suppress the voltage in the plasma above the interconnect to a value less than the bias voltage. Hence, the current collection area is limited to the interconnects.

Above 100 volts bias, there is a transition in the characteristics of the surface voltage. The quartz cover slide potential changes to a value that is about 50 volts less than the bias voltage. It is as if the voltages in the interconnect region had "snapped-over" encompassing the cover slides. This occurs due to the interconnect

electric fields accelerating plasma electrons into the quartz cover slides with sufficient energy to generate secondary electrons. These secondary electrons are collected by the interconnects causing the rise in the electron current collection. The quartz cover slide surface voltage must increase to compensate for the secondary current contributions.

For the negative bias cases (see fig. 6(b)) there is an abrupt transition into an arc discharge between the metal interconnects and the surrounding space. The voltage at which arcing occurs is plasma-density dependent. At densities of $\sim 10^4 \text{ cm}^{-3}$ (low Earth orbit) this arcing occurs above -500 volts. At densities of $\sim 30 \text{ cm}^{-3}$ (geosynchronous altitudes) arcing occurs above -5000 volts. For bias voltages below these arc threshold values, the ion current collection remains relatively small, at values expected from probe theory.

The reason for the negative voltage behavior can be found in the surface voltage traces (see fig. 7(b)). As negative bias voltages are applied to the segment, the quartz cover slides again assume a slight negative surface voltage to maintain the required current balance. The electric fields in the plasma due to the bias voltage are therefore confined to the region of the interconnects as before. As the bias voltage is increased, the quartz surface voltage continues to confine the interconnect voltages until the electric field existing in the cavity formed by the quartz cover slides and interconnect becomes so strong that a discharge can be triggered by field emission from the interconnect.

The characteristics of the interactions described here have also been observed in a space flight experiment called PIX, an acronym standing for Plasma Interaction Experiment (ref. 19). This experiment was flown on the Landsat C launch, March 5, 1979 and operated in a 900 km polar orbit for over 4 hours. Bias voltages of up to ± 1000 volts were applied to a 100 cm^2 solar array panel. The anticipated transition in electron current collection and the breakdowns at negative voltages were recorded.

Coupling currents observed in ground simulation tests using a 2000 cm^2 solar array panel are shown in figure 8. For positive bias voltage cases the transition in electron current along with the same type of area dependence discussed earlier was measured. The influence of test chamber size was observed while these tests were being conducted. The plasma in these chambers was limited by the finite volume of the chamber. When the solar array panel was biased to a value where all the available plasma electrons were collected, the coupling current saturated (i. e., remained relatively constant as the bias voltage was increased). In this test this limiting voltage was found to be about 200 volts. This chamber size limitation emphasizes the need to conduct large sample, high voltage surface tests in space.

For the negative bias voltage cases, the ion current collection remained low and fairly linear with voltage until the bias exceeded -500 volts at which the transition that terminates in arcing occurred.

The SEP array segment test results are shown in figures 9(a) and (b). This segment had a Kapton substrate in which holes were cut to make the joints between the solar cells. Both front and back side voltage distributions are shown in figure 9(a). The snap-over phenomenon is evident on both sides at positive bias voltages as is the confinement at the negative bias voltage. Figure 9(b) shows the dis-

charges that were photographed during this test. The light flashes correspond to the discharge points and always occur in the interconnect cavity or in the holes cut in the Kapton substrate.

Summary of Test Results

Based on the ground simulation testing one should expect that the insulator surfaces surrounding the biased conductors would influence the interactions with a charged-particle environment. For areas of a high voltage, solar array space power system that are at potentials greater than 100 volts relative to the space plasma potential, electron current collection should be proportional to the interconnect and cover slide area. For areas of the array that are negative with respect to the space plasma potential, current collection is limited to interconnect areas and arcing can occur. This arcing threshold is between -500 - 1000 volts in low Earth orbits and between -5000 and -10,000 volts at geosynchronous.

ANALYTICAL MODELLING OF LARGE, HIGH-VOLTAGE

SPACE POWER SYSTEMS

There have been analytical studies assessing the impact of charged-particle environment interactions on high-voltage space power systems (refs. 23-25). In this report the modelling is done in the NASA Charging Analyzer Program (NASCAP) code which was originally developed for the spacecraft charging investigation. The advantage in using this code is that it treats in a self-consistent manner the material's response to environmental particle fluxes. Hence, this code can compute the current collected by the biased conductors (using orbit-limited probe theory) and also compute the dielectric surface voltages. While the code can treat many of the characteristics of these high voltage system, it can not yet handle all interactions. Even so, it can indicate areas where design techniques must be developed if these high-voltage space power system are to be feasible.

NASCAP High-Voltage System Model

NASCAP Description. - The NASCAP code has been described previously in the literature (refs. 27-30) and can be briefly summarized here. NASCAP is a quasi-static computational code (i. e., it assumes that currents are functions of environmental parameters, electrostatic potentials, and magnetostatic fields while not dependent on electrodynamic effects). It is capable of analyzing the charging of a 3-dimensional, complex body as a function of time and system generated voltages for given space environmental conditions. It includes consideration of the

dielectric material properties (e. g. , secondary emission, backscatter, photo-emission, and bulk and surface conduction) and computes currents involving these materials in determining the potential distributions around the body.

The body must be defined in terms of rectangular parallelipeds or sections of parallelipeds within a $17 \times 17 \times 33$ point grid. The body must be at least 1 grid cell thick in the version of the code used here. Only seven separate conductors can be specified in the code. The first conductor must be floating relative to space while the other six can be biased relative to the first.

The environment can be defined in terms of Maxwellian distributions by specifying the plasma densities and temperatures (in volts). Both normal and geomagnetic substorm environments appropriate to geosynchronous orbits can be used.

The code output includes a variety of graphical and printed data displays. Graphical output includes the material and perspective object definition plots, potential contour plots and particle trajectory plots. The printed output includes a summary of all cell voltages, listings of currents to specified surfaces and compilation of electric fields through the dielectrics, listed in decreasing order.

High-voltage system model. - The NASCAP model of the high voltage space power system considered in this report is shown in figure 10. This system consists of two solar array wings, each $50 \text{ m} \times 60 \text{ m}$, with a central, 20 m octagonal antenna. This antenna (center body) is assumed to have an aluminum top and bottom while the sides are covered with 0.01 cm thick Kapton. This body is the first conductor and is the system electrical ground even though it is floating relative to the space plasma potential.

Each solar array wing is assumed to be divided into three sections, $20 \text{ m} \times 50 \text{ m}$, with each section operating at 7000 volts. The interconnects are assumed to be aluminum and exposed on the front and back of the array similar to the SEP array design. Since the NASCAP code can not treat small gaps, the interconnects are assumed to be concentrated at two locations in each section as shown. This exposed area represents 5 percent of the front and back areas of each section. This is a reasonable approximation for the exposed interconnect areas. Quartz cover slides, 0.015 cm thick are used for the solar cells. The substrate and sides of the array are covered with 0.01 cm thick Kapton.

The electrical circuit for this power system is assumed to be such that there is a 42 kV potential difference across the array (see fig. 11). The overall power output of this system is on the order of 600 kW with each section generating 100 kW.

Analytical Model Computations

The behavior of this system is analyzed in a normal geosynchronous environment having plasma densities of 10 cm^{-3} and particle temperatures of 1 eV. The array is assumed to be in full sunlight and only steady-state conditions are considered. The difficulties that may be encountered during eclipses and geomagnetic substorms will be left for future analysis.

Prior analytical treatment of high voltage systems with the NASCAP code indicated that the "snap-over" phenomenon at positive voltages greater than 100 volts

did not automatically result from the code operation (ref. 31). However, it could be simulated by allowing the insulator surfaces to have a low surface resistivity. A value of surface resistivity of 10^5 ohm/square was assumed to be appropriate and used for the quartz and Kapton substrate surfaces of the most positive-voltage section only.

The voltage distributions in the space around the system are shown in figure 12. These diagrams show a view of the top of the array and an edge view through the center of the array. As expected, the operating voltages used here have forced the antenna to float at a very negative value (-17.9 kV) and have established negative voltage distributions around most of the system. Large voltage concentrations are seen to exist at the simulated interconnect regions.

These voltage distributions are shown in more detail in figure 13. Note that only one section of the array has remained positive (+3.1 kV) and that the positive voltage distributions in space are extremely limited. This result was obtained under the assumption that only the most positive voltage wing section had low surface resistivity. Trial runs made assuming that all positive-operating voltage sections had low resistivity resulted in the +7 kV and +14 kV sections remaining negative relative to space. Hence, only the 21 kV section should be experiencing the "snap-over" phenomenon.

A view of the system sectioned through the interconnects showing the end-to-end surface voltage profile is given in figure 14. This voltage profile indicates that the quartz surface voltage on the negative-voltage wing remained at about -6 to -7 kV while the conductive interconnects were at -25 to -39 kV, giving rise to electric fields of 1 to 2×10^6 V/cm. At these electric fields, arcing will occur. On the positive-voltage wing the fields at the interconnects are on the order of 10^5 V/cm. It is possible that arcing could occur in the first section (-10.9 kV). The absolute criteria for breakdown still has to be determined.

The simulation of the "snap-over" phenomenon is also shown in figure 14. The use of surface conductivity provides a reasonable approximation of this "snap-over" phenomenon but additional work still is required to improve this simulation.

The plasma coupling current collected by this system is on the order of 0.1 ampere, less than 1 percent of the bus current. Hence, this study substantiates the previous conclusions that power losses in geosynchronous orbits is not a serious problem.

The electric fields through the dielectrics are shown in figure 15. These fields are very strong and can produce mechanical stresses in the dielectrics. The force per unit volume induced in the dielectrics is given by:

$$T = \frac{1}{2} \vec{D} \cdot \vec{E} = \frac{1}{2} \epsilon_0 E^2 \text{ newtons/m}^3$$

where

ϵ relative dielectric constant

ϵ_0 permittivity of space (8.85×10^{-12} coulomb²/newton \cdot m²)

These volume forces range from 3 to 50 newtons/m³ and must be considered in designing these systems.

Finally, the question of energy storage in these dielectrics must be considered. At the predicted voltages, the energy capacitively stored in the dielectric surfaces is on the order of megajoules. From the spacecraft charging investigation it is known that the discharge of a few joules of energy, capacitively stored in spacecraft surfaces, can disrupt electronic surfaces and degrade thermal control surfaces. A discharge in the high voltage system of even a fraction of this stored energy could be catastrophic. Since there is insufficient data on discharge phenomena to determine if such a breakdown could actually occur and how much energy would be lost, then additional studies are required to evaluate this possible threat.

Discussion of Results

In its present form, the NASCAP code is not a perfect tool for analyzing interactions between high voltage solar arrays and charged-particle environments. But, it does include the dielectric materials in the computations of the voltage distributions around the object. Hence, the code can be used as a valid indicator of technology needs for understanding these interactions.

This study indicates that the first barrier to overcome in the use of high voltages for space applications is the arcing in the negative-voltage wings. Since the array must float predominately negative relative to space, there will be the possibility of such arcing. This phenomenon is amenable to solution providing that a technology effort is undertaken to suppress such arcing. Such suppression has been found for switch-gear and is being found for spacecraft charging type discharges.

The possible difficulties with induced forces and energy storage in the dielectrics can also be overcome by a technology effort. If the electric fields could be reduced, then the force and energy storage would be diminished. Reduction of electric fields could be accomplished by a change of materials or by reducing the resistivity of dielectrics proposed for these systems. These changes could increase the coupling currents so that trade-off studies must be conducted.

An improved analytical tool is required in order to assess better the interactions. Since these systems are large, ground simulation testing will continue to be limited to small samples and will be geared more toward understanding processes rather than demonstrating system feasibility. Extrapolations from test articles to complete systems and from vacuum facility simulations to space environments must be done with this analytical tool.

The above problems and the means leading to their solution are the areas in which logical concern should be expressed for high voltage system operation in space. The interactions are not insurmountable, they are not ultimate barriers to the use of high-voltage space systems. But, they must be faced, studied and understood.

CONCLUDING REMARKS

Large, high-voltage space power systems are being proposed for future applications in both low Earth orbit and geosynchronous altitudes. These systems will have exposed conductive surfaces that will be at various voltage levels relative to the space plasma potential. These conductive surfaces will be surrounded by thin dielectric surfaces such as quartz or Kapton. The space charged-particle environment will interact with these complex conductor-insulator systems influencing the system performance.

Ground simulation testing has indicated that when solar array circuits are biased to voltages greater than +100 volts, the electron current collection is enhanced. It is believed that the bias field accelerates plasma electrons into the cover slides generating secondary electrons which are collected. When solar array segments are biased to large negative voltages (>500 V), arcing occurs. This arcing appears to be confined to cavities such as those formed by cover slides and interconnects or in holes in the substrates. Both of these phenomena are plasma density dependent.

A preliminary analytical model of a high voltage space power system has been developed using the NASCAP code. The performance of this system operating at 42 kV is analyzed in geosynchronous environmental conditions. This analysis indicates that the system would float about 3 kV positive and 39 kV negative relative to the space plasma potential. Under these conditions the power lost through the environment is less than 1 percent as expected. However, electric fields within the dielectrics (0.015 cm quartz cover slides and 0.01 cm Kapton substrates) and at the interconnects are in excess of 10^6 V/cm giving rise to breakdowns. These electric fields also can induce strong mechanical forces within the dielectrics and store considerable energy in the dielectrics. These could cause difficulties in the proposed long lifetime of these systems.

The existing ground test data and analysis strongly indicates severe detrimental interactions between high voltage systems and charged-particle environments. These interactions are not believed to be insurmountable. The data and studies are based on present day construction techniques and materials choices. With a technology investigation to understand the interactions, it will be possible to devise means of controlling these interactions, and of guaranteeing the successful operation of high voltage space power systems.

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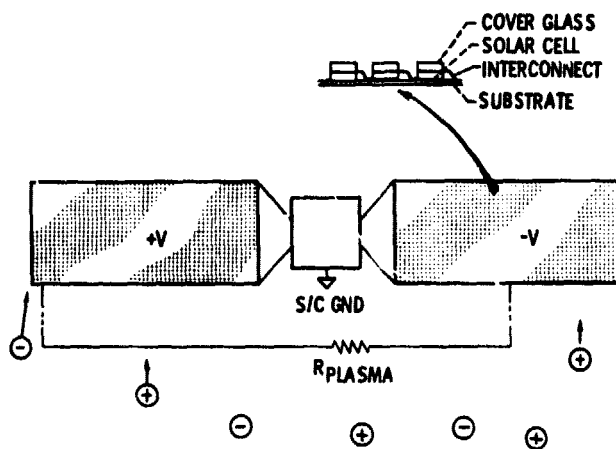


Figure 1. - Spacecraft higher voltage system-environment interactions.

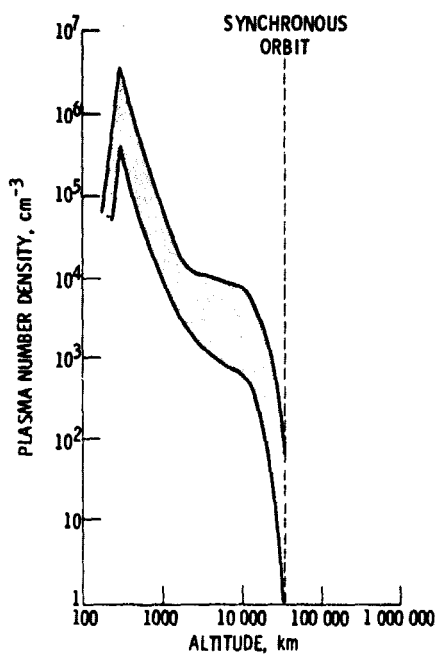
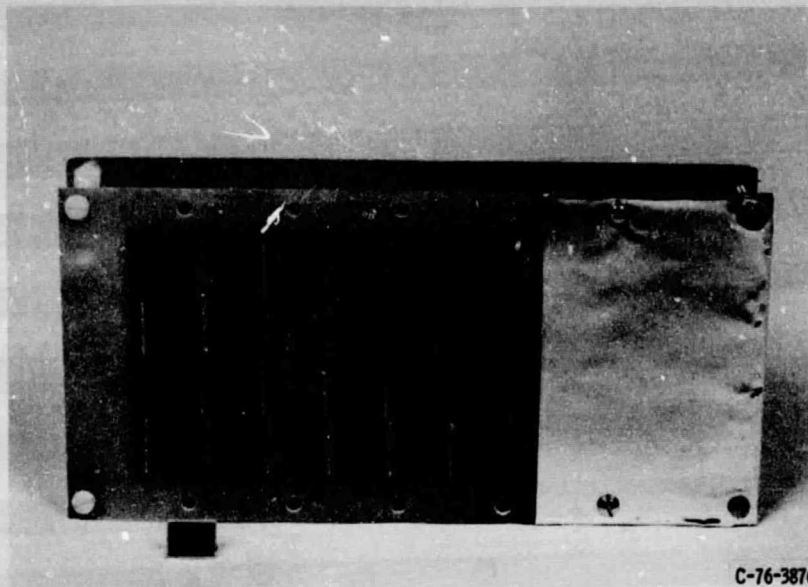


Figure 2. - Plasma number density vs altitude in equatorial orbit.

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Figure 3. - Solar array segment

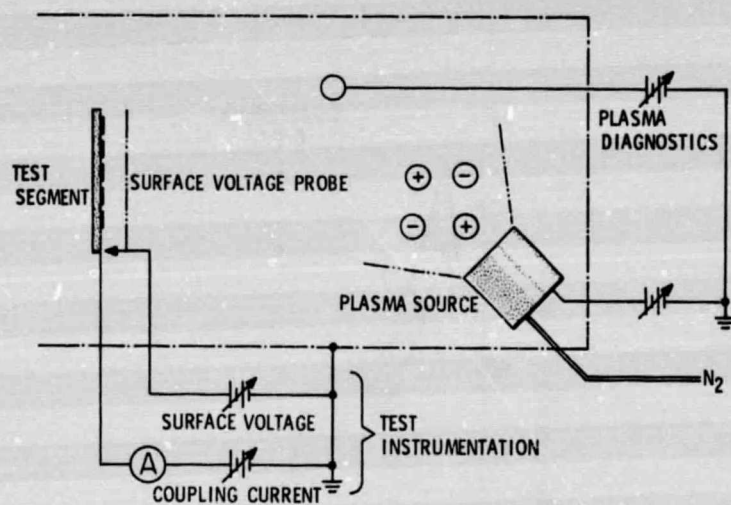


Figure 4. - Schematic diagram of test arrangement.

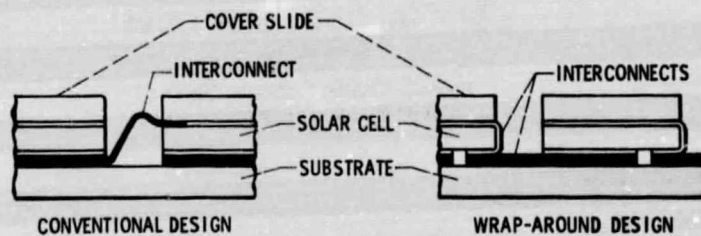
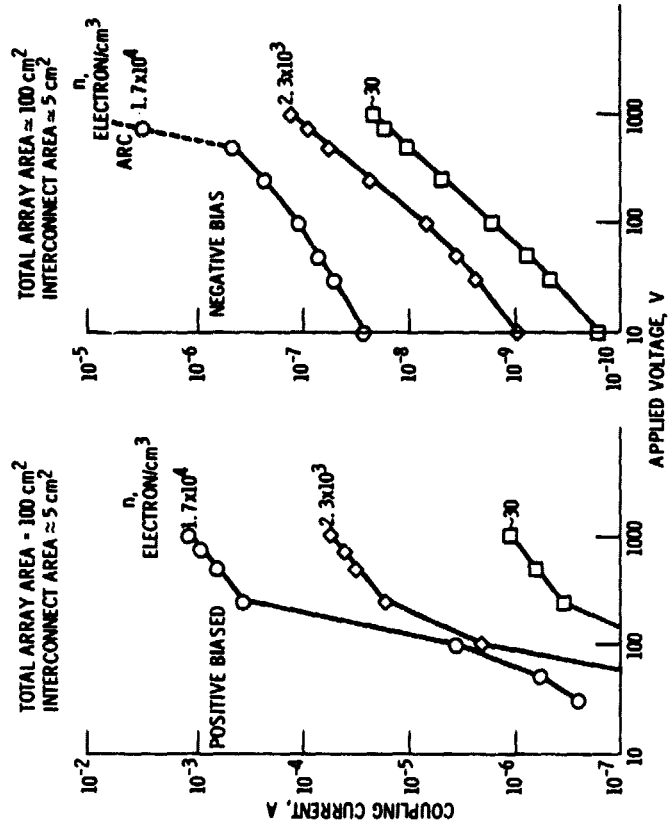


Figure 5. - Solar array interconnect configurations.



(a) POSITIVE BIAS. (b) NEGATIVE BIAS.

Figure 6. - Plasma coupling currents for 100 cm² solar array.

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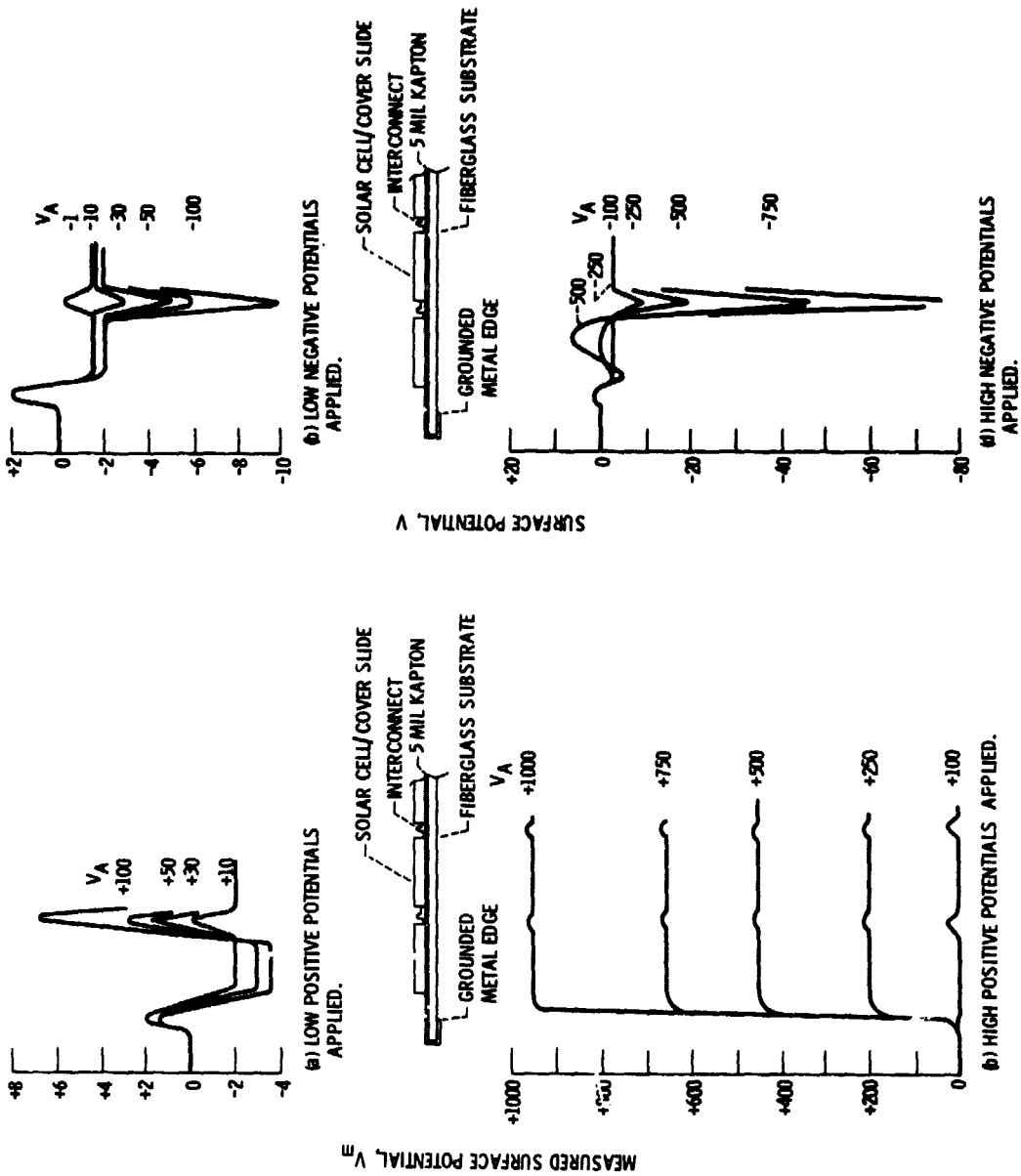


Figure 7. - Typical surface voltage profiles-solar array segment.

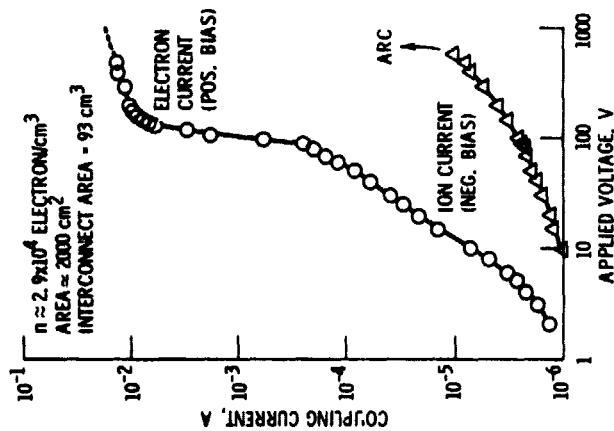
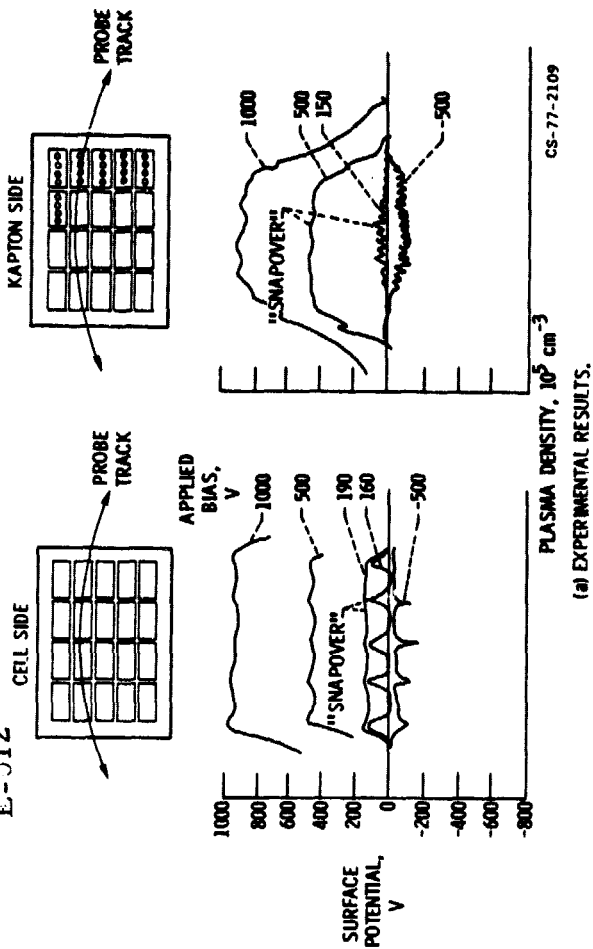


Figure 8. - Plasma coupling currents.
Large solar array panel.

ARCING ON SOLAR CELL ARRAY SAMPLES
2x4 cm WRAPAROUND CELLS ON KAPTON
-1 kV BIASED ARRAY CIRCUIT
 10^5 cm^{-3} N PLASMA (25 eV IONS, 3 eV e^-)

NASALEWIS RESEARCH CENTER
ENVIRONMENTAL INTERACTIONS PROGRAM
(b) PICTURES OF ARRAY (COMPOSITE).

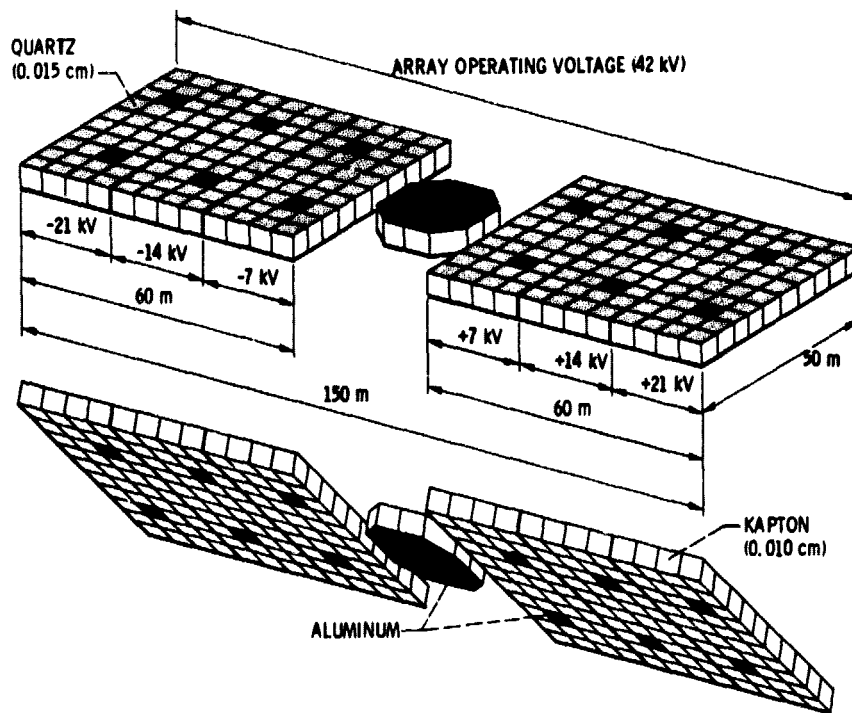


Figure 10. - NASCAP model space power system.

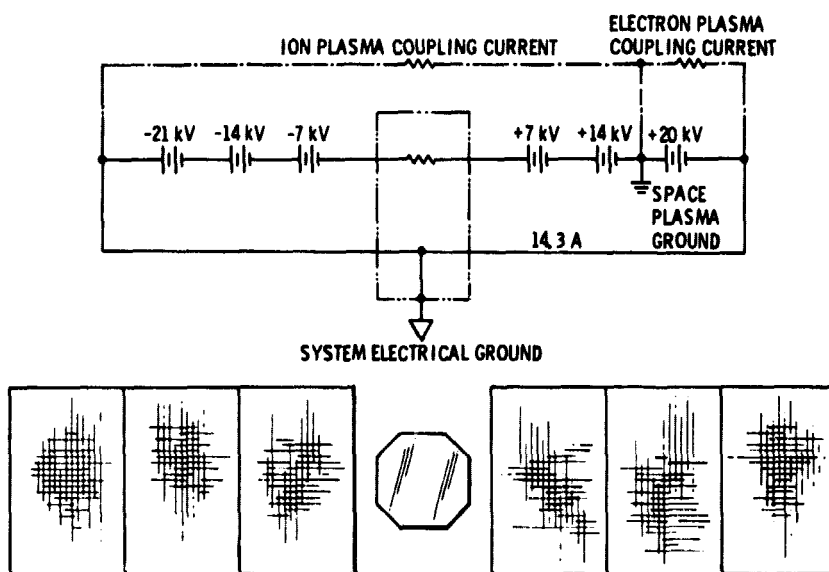


Figure 11. - Schematic diagram of high voltage power system ion plasma coupling current.

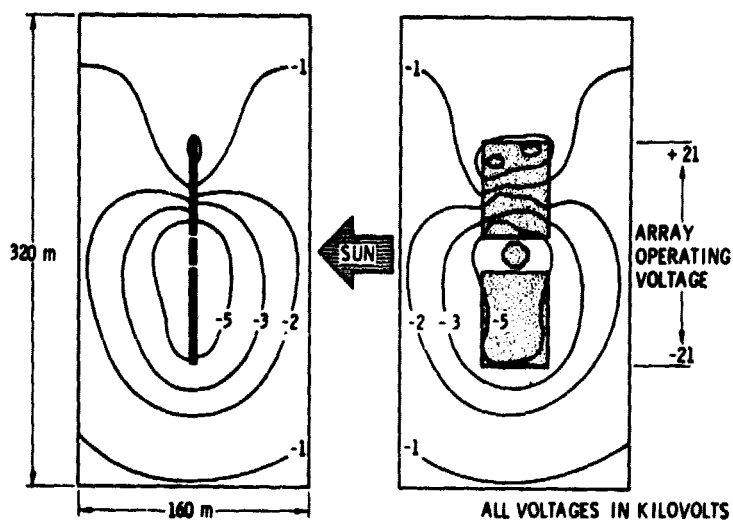


Figure 12. - Voltage distribution around power system. (System ground at -17.9 kV relative to space.)

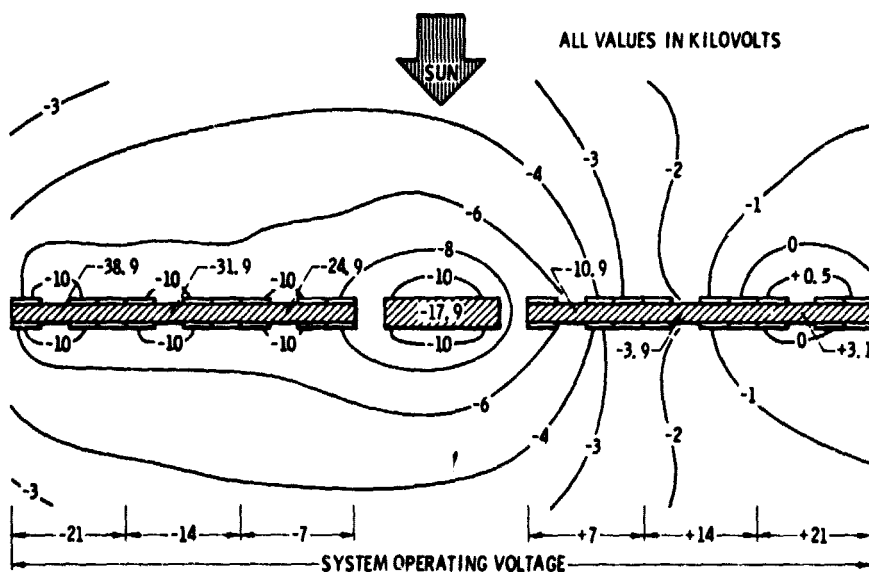


Figure 13. - Voltage distribution around space power system. (Relative to space plasma potential.)

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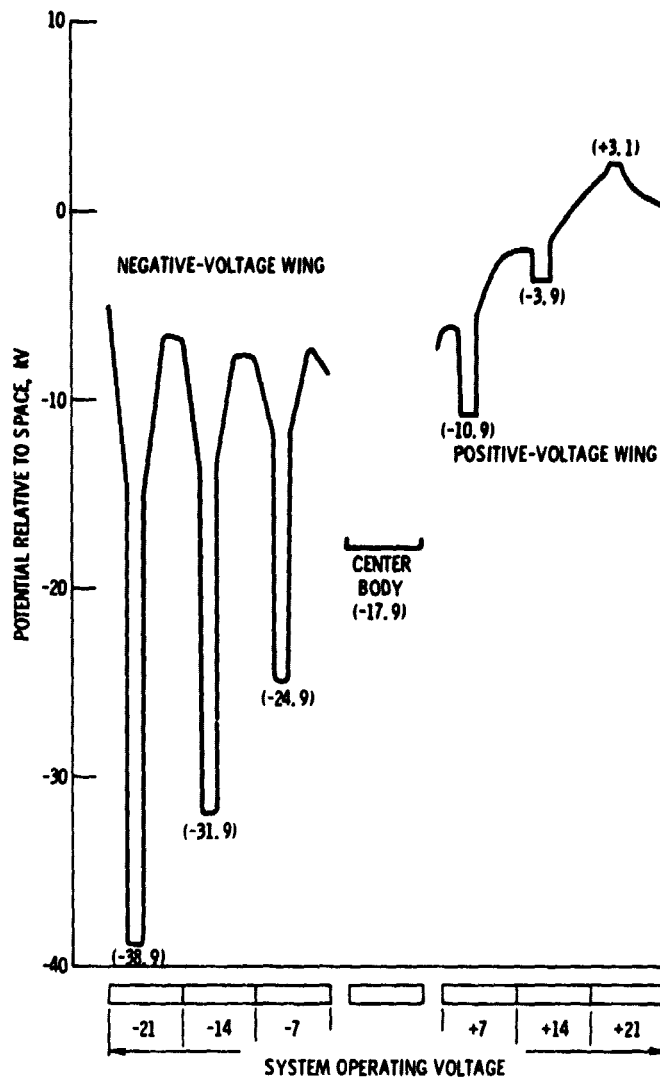


Figure 14. - Potential profile across sunlit surface. (Relative to space plasma potential.)

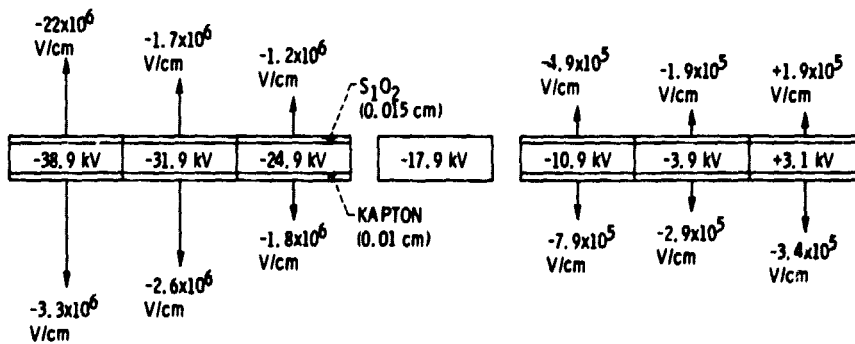


Figure 15. - Electric fields in dielectric materials. High voltage power system.

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